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The NCPV Process Integration Project: Purpose, Status and Direction

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The NCPV Process Integration Project: Purpose, Status and Direction

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ABSTRACT

The primary purpose of the process integration project of the National Center for Photovoltaics (NCPV) is to develop an infrastructure that will allow researchers to gain new knowledge that is difficult—if not impossible—to obtain with existing equipment. This difficulty is due, in part, to the state of our existing tool set, which lacks sufficient in-situ or real-time measurement capabilities, or lacks access to analytical tools where the sample remains in a controlled environment between deposition and processing or measurement. This new infrastructure will provide flexible and robust integration of deposition, processing (etching, annealing, etc.), and characterization tools via a standardized transfer interface such that samples move between tools in a controlled ambient. The standardization of control and data acquisition software schemes, sample handing, and equipment components will allow us to perform research more efficiently; facilitating collaborations and technique development.

INTRODUCTION: PROCESS INTEGRATION NEEDED

Process integration has been the key to the rapid advancement of the integrated circuit (IC) industry [1], which works with similar materials as the photovoltaics (PV) industry. In IC industry case, the various manufacturers came together to develop tool standards and integration schemes that were shared across the industry. In this way, they were able to drive the direction of tool fabricators to meet the needs of the entire industry. This is not to say that they shared all their manufacturing details. A useful analogy might be that they shared kitchen designs, appliances, and ingredients, but not the recipes or family secrets. The integrated-circuit industry had two distinctive advantages in accomplishing their process integration: they handle only one type of material—silicon wafers—and they have much greater financial resources with which to influence tool development. One of the keys to the success of the IC industry was the creation of mini-environments, in which the industry significantly reduced the contamination of wafers between processing steps [2]. The standard mechanical interface (SMIF) pods are used to enclose and transport wafers between 200-mm tools; the newer front-opening unified pods (FOUP) are used on 300-mm tools. Wafers are taken from one tool, loaded into these mini-environments, and transported in a clean ambient to another tool. These mobile pods are usually filled with clean air or inert gas.

The PV program within the National Renewable Energy Laboratory (NREL) has advanced through focused efforts in materials growth and processing, development of novel device design, and the measurement and characterization of materials and devices. However, the continued success of the NREL PV program will require the integration of these research areas similar to the steps taken by the IC industry. The National Center for Photovoltaics (NCPV) has realized this need for a long time [3]. The III-V group at NREL has successfully used an integrated metal-organic chemical vapor deposition (MOCVD) chamber, a molecular-beam epitaxy (MBE) chamber, and a surface science chamber for a number of years. By having integrated deposition and characterization and being able to transfer samples between chambers under ultra-high vacuum (UHV), researchers have been able to investigate the stability of surfaces [4] and surface reconstruction processes [5], among other things. The most recent example of integrated chambers is in the surface analysis group. The group has four chambers integrated via a UHV track transfer system, giving them X-ray photoelectron spectrometry (XPS), Auger electron spectrometry (AES), and PVD capabilities, as well as integration to a glove box for loading samples, wet etching, and chemical bath depositions (CBD). All in all, there are fewer than 20 chambers integrated on 8 different platforms. These early attempts at integration make up less than 10% of the capabilities within the NCPV. The remaining systems are comprised of designs that do not lend themselves to being integrated with any substrate form factor. While most of these systems have the requisite instrumentation (measuring pressure, power, flow, temperature, etc.), most are manually controlled. Some are computer controlled, but the computer systems are dedicated to that tool and may use propriety software making it difficult to get the data out of that workstation. Only a few of these systems are “recipe driven,” following a data transfer protocol that lends itself to full automation.

The main design goals of the NCPV Process Integration project are to:

- Develop a standard sample transport between tools
- Ensure the sample transport mechanism is robust
- Control the ambient of that sample transfer
- Be able to deposit uniformly and reproducibly over areas large enough to be meaningful to industry
- Handle a wide variety of sample substrates
- Standardize control and data logging software
- Integrate as many techniques as practical [6].

APPROACH: THE PATH TO PROCESS INTEGRATION

There are four foundations to an integrated tool set:
(1) Hardware: being able to pass samples between tools
(2) Software: integrated control and data acquisition
(3) Peopleware: collaboration on common goals
(4) Facilities: providing proper space and utilities.

Hardware Standards

We will integrate individual deposition, processing, and characterization techniques via one of several different modes. Ideally, characterization techniques will be used for real-time analysis of materials or surfaces during deposition or of the process itself. The next best solution is in-situ analysis of materials or surfaces. When neither of these integration methods is possible, techniques will be integrated by transferring samples from one location to another, either via intra-tool or inter-tool sample transport. Intra-tool transport is the movement of samples between techniques within the same set of interconnected chambers, that is, a cluster tool. The actual transfer mechanism could be robotic or a linear track transport mechanism. Inter-tool transport is the movement of samples between techniques, where those techniques do not share direct connection. Integration types are summarized in Table 1 and a schematic representation is provided in Figure 1.

Table 1: Integration Modes: Measurement Apparatus to either Deposition or Processing Apparatus

Meas. Class	Transport Ambient	Meas. Local	Meas. Ambient	Meas. Timing
Real-Time	X[1]	same chamb.	fixed[2]	during process
In-Situ	X[1]	same chamb.	fixed	post or interrupted
Intra-Tool[3]	fixed	same tool	fixed	post deposition
Inter-Tool[4]	fixed	diff. tool	fixed	post deposition
Mobile[5]	fixed	mobile	fixed	varies w/ technique
Ex-Situ, air trans.	air	diff. tool	fixed	post deposition
Ex-Situ, air meas.	air	diff. tool	air	post deposition

1 In-Situ: Latin for “in the original place.” Real-time diagnostics are a sub-set of in-situ. Once a sample is moved from the original place (chamber), it is an ex-situ measurement, even if it is within the same tool.
2 A fixed ambient is controlled—e.g., Ar, UHV, etc.—as opposed to an uncontrolled ambient such as lab air.
3 Intra-tool transport is the movement of samples between techniques within the same set of interconnected chambers (i.e., the sample transfer within a cluster tool) [7].
4 Inter-tool transport is the movement of samples between chambers lacking a direct connection (i.e., independent cluster or stand-alone tools) [7].
5 A mobile technique is within a chamber that can be moved between tools for a fixed set of experiments.

Techniques integrated via an inter-tool transport could be in a stand-alone tool or a part of a cluster tool. The sample is moved from one tool into the pod, which is sealed and disconnected from that tool before being wheeled to another tool where the process is reversed. While this approach is similar to that used in the IC industry, the transfer ambient within our pod must be either an atmosphere of ultra-high-purity inert gas or high vacuum. These environments are much more difficult to maintain than the “particulate free air” requirement of the SMIF pod or FOUP [2].

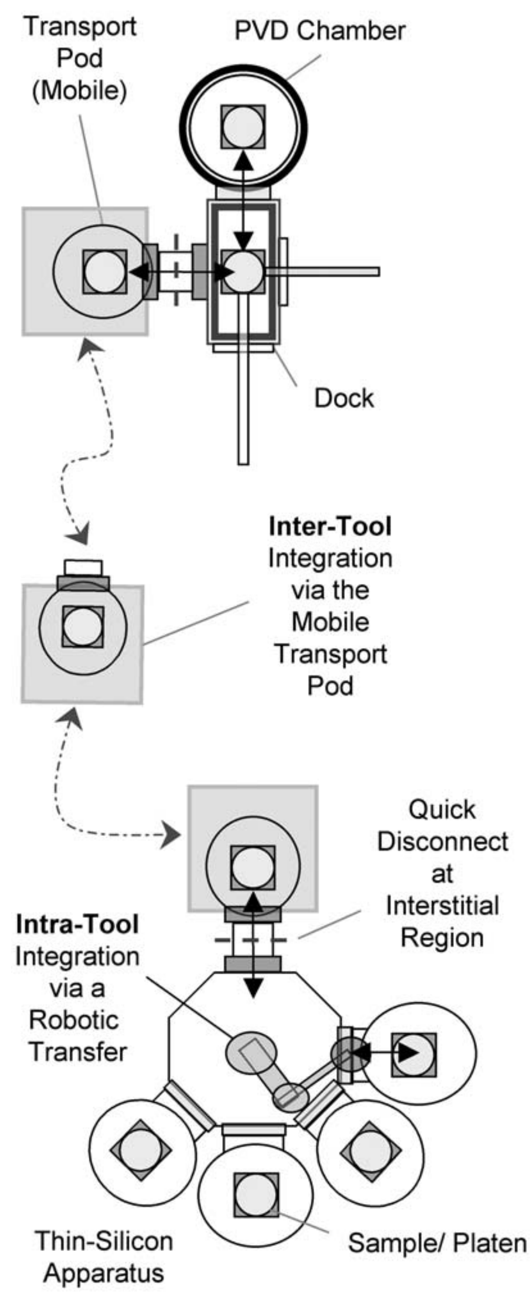

Figure 1: Schematic of inter-tool and intra-tool integration of equipment; a stand-alone tool at the top and a four-chamber robotic cluster tool at the bottom.

Design standards are necessary to build a collection of integrated tools. Most of these hardware elements are represented in Figure 1 and briefly described below.

The platen drives the requirements for the entire design. We have set the maximum substrate size the platen can handle to be 6.18” X 6.18” (157 mm X 157 mm). This size supports the silicon photovoltaic industry, which has a “6-inch square” protocol in multi-crystalline and a “6-inch round” protocol in single crystalline. It is also a good size for the various thin-film technologies, as it is large enough to demonstrate commercially viable processes, yet not so large as make tool and substrate costs prohibitive. The outside dimension of 7” X 7” will accommodate a variety of platen designs to allow for different substrates, such as soda-lime glass, high-temperature glass (e.g., Corning 1737), crystalline wafers (e.g., Si, Ge, GaAs), thin stainless steel, ceramic, and exotic materials (e.g., plastics and thin foils). Individual researchers will be able to use platens that hold smaller substrates, but must be able to accept the standard size in their tool. In specialized cases, a smaller platen will be “piggy-backed” onto the standard platen for loading into tools that cannot be built to accept the standard size. The platen itself must be able to withstand temperatures in excess of 800ºC; therefore, construction material will be molybdenum, Inconel, or similar material.

In Figure 1, the chamber that moves from tool to tool is referred to as the transport pod; it provides the inter-tool transport between independent tools. It contains a cassette capable of securing up to six platens for transport between tools. A quick connection between the transport pod and the tool occurs in the “interstitial region,” allowing the pod to be separated from tool and moved to another. There is a valve on both sides of this interstitial region to reduce air exposure to both the pod and the tool. Once a pod is connected to a tool, this interstitial region is evacuated before any transfer occurs.

The dock is the design element that houses the transfer mechanism for introducing platens into either a stand-alone chamber or a transport pod. With the transfer mechanisms housed in the dock, both the stand-alone tools and transport pods are free of internal transfer mechanisms. The dock contains a cassette capable of queuing up to six platens for use in a given tool.

The first stand-alone tool built to these process integration standards for the NCPV combines a PVD chamber, a dock, and a pod. It will allow us to test heater designs for uniformly heating the standard platen to ~800°C and be used for sputtering of metals and transparent conducting oxides. This tool will also contain a flipping station to allow samples to be loaded into a cassette, either film-side up or film-side down for different applications.

A robot moves a platen from chamber to chamber in Figure 1, thus providing the intra-tool transport within that cluster tool. Another way to connect independent chambers is to have a long chamber with a track or trolley system and stopping points where a separate mechanism moves the platen orthogonally from the track to a given chamber. There are advantages and disadvantages to each transfer mechanism, as described in Table 2. The first cluster tool built to these process integration standards for the NCPV will be a robotic cluster tool to support silicon work (e.g., thin-silicon and silicon-nitride growth).

Table 2: Cluster Tool Platform Comparison

Consideration	Track Transfer[1]	Robotic Transfer[2]
Transfer Automation	– Difficult to automate	+ Designed to automate
Throughput[3]	– Low: Limited automation	+ High: Full automation
Robustness	– Each one is a unique design	+ MTBF ~80,000 hours
Footprint	– Larger: Uses up lab space	+ Smaller: Saves lab space
Expandability	• Add modular sections[4]	• Robot-to-robot handoff[5]
Instrumentation Space Available	+ Large ch. to ch. distance	– Tight chamber clusters
Maintenance Access	+ Easy, ch.s are spread out	– Difficult, ch.s are packed in
Vacuum Level in Transfer Zone	+ 10^{-10} Torr best – Move in min.s	– 10^{-8} Torr best + Move in sec.s

1 A linear transfer along a “spine” where tools are accessed perpendicularly via a secondary mechanism.

2 Process chambers around a centralized chamber--with a circular form factor--containing a robot arm.

3 Throughput is a separate issue from automation, if the time between processing steps needs to be short.

4 If space is available, expandability is easy by adding a hand-off station to the “end of the line.”

5 Once all ports are full, a new robotic chamber needs to be connected via one port, losing a chamber to hand-off on the existing robot, but adding n-1 ports, where n = ports on new robot.

Software Standards

The IC industry has learned that the integration of control and data acquisition software is important and time consuming [8]. Efforts to create “plug and play” integration of manufacturing tools and data are under way within the IC industry [9] and are being addressed as a part of this project. Specifically, the use of recipe/run control using XML-based data transfer. This is a minimal set of CAMX protocols implementing the sending of recipes from a central database. The tool writes back to the database actual readings from the process.

Peopleware

The Process Integration Project Engineering Team meets regularly with representatives from research groups throughout the NCPV to discuss all design features. Typically, these meetings focus on a particular design area, with a core group concentrating on each aspect. When a key decision is reached, the appropriate focus group gathers consent from their existing research team and then signs off on the appropriate aspect of the project. These focus groups tend to concentrate on the fine detail of the project.

An Umbrella Group was formed with representatives from the core research areas within the NCPV to ensure that the project is compatible with future needs. This group gives guidance and signs off on all process integration tool purchase requests. They weigh the big picture of the project, considering overall integration and functionality.

An Advisory Group was formed with research collaborators from industry to ensure that the project is compatible with their future collaborative research needs. This group gives guidance to the project and provides feedback to their respective organization, including project status and soliciting ideas as to how they can best use this new infrastructure in future collaborations.

Researchers within the NCPV, as well as their university and industrial collaborators, will have access to the project's design standards. Partners can then build their tools so that they can be integrated to other tools and thus maximize the integrated tool collective. Eventually, researchers from outside NREL will be able to build modules to the standard, bring them to NREL, and leverage their new experiment with the existing integrated tool base. Such collaborations will foster student and sabbatical placements.

Facilities

The main thrust of this project is to give the NCPV staff the right tools. However, NREL personnel are also working diligently on the construction of a new building, the Science and Technology Facility, which will provide optimal facilities for an integrated set of tools. Construction is planned to start in February 2005, with the building being ready for occupancy in late fall of 2006. This facility will provide large open laboratory space to ease inter-tool transport. It will also provide state-of-the-art utility services, such as centralized (house) hydrogen, nitrogen, and argon. The laboratory areas are built to international building code standards as an H-5 facility for semiconductor fabrication and comparable research and development using hazardous production materials.

CONCLUSIONS

We have achieved remarkable consent from individuals with a diverse spectra of research interests in the development of these process integration standards. In the next few years, we will have significantly improved the tool base for collaborative research within the NCPV. The modular nature of chamber construction will add to flexibility in cluster tool arrangement and foster collaborations. Having standard designs should reduce engineering and development costs of future tools. Having standard components should reduce spare part inventories, speed repairs, and increase operational efficiency, thus allowing researchers to focus more on science.

The process integration concept will also require the cooperation of experts from various material technologies and characterization disciplines to work with each other to answer key scientific and technological questions. Ultimately, this synergistic effort between NREL staff, universities, and the photovoltaic industry—around an integrated tool base—will add to the PV knowledge base and help move PV technologies forward.

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